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Research Article

Fault Tree Model of Collapse Bridge and Risk Analysis of Hassanabad Bridge

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Abstract

The catastrophic and widespread floods that hit Pakistan in May of 2022 seriously and extensively damaged the social infrastructure and lifelines. Using specific scenarios that may be utilized to quantitatively and explicitly assess the damage status and the cause of the damaged bridge groups may be helpful in solving structural and challenging engineering challenges. These kinds of cases can help improve future bridge designs and construction methods by identifying the causes of the breakdown and the scope of the investigation. They may also bring about a flood that destroys the bridge. One of the biggest infrastructure tragedies is a bridge catastrophe. This study examines bridge infrastructure risk from the standpoint of sustainable management. Pakistani bridge disasters demonstrate that anthropogenic forces are mostly to blame for these failures. The collapse of the Hassanabad Bridge on 07 May 2022 in Hunza Tehsil of Gilgit-Baltistan region of Pakistan Occupied Kashmir (POK), Pakistan is used as a case to perform detailed analysis. Superficially, bridge collapse is a technical problem rather than a management problem. The study recommends the glacier has an anomalous behavior, it is necessary to monitor the glacier and Glacier Lake continuously, and minimize the adverse effects of potential GLOFs risk. We also recommend strong understanding the phenomenon of glaciers therefore, glacier lakes are very important in north Pakistan with respect to GLOF disaster management. Yet, the main reason for this kind of bridge failure may be a lack of sustainable management and the Glacier Lake outburst. In order to support this viewpoint, both a fault tree analysis (FTA) and a strategic environmental assessment (SEA) for the bridge failure and subsequent effects on society are conducted. According to the FTA data, the Hassanabad Bridge's collapse was caused immediately by the failure of the arch foot. An in-depth examination of management issues pertaining to the economy, culture, human health, and environmental sustainability is done through strategic environmental assessment (SEA). Bridge collapse is likely caused by a lack of real-time monitoring, poor risk assessment, and other management issues. The low overall SEA result makes it clear that the project was poorly managed and that there was an excessive safety risk. Finally, the specific managerial measures are proposed to improve the sustainability of infrastructures.

Keywords: *Bridge Failures; Hassanabad Bridge; Fault Tree Analysis (FTA); Strategic Environmental Assessment (SEA); Safety Risk; Sustainability*

1. Introduction

Due to its quick industrialization, Pakistan had to build the infrastructure required for the transportation of goods and raw materials after gaining independence. A huge network of roadways with integrated bridges and flyovers resulted from this. Several old bridges in Pakistan and other nations are beginning to exhibit problems well before the end of their anticipated service life, frequently as early as 10 to 20 years after construction [1-2].

Poor construction quality, corrosion of the steel in reinforced concrete bridges and pre-stressing cables in pre-stressed concrete bridges, improper design and detailing for normal loads and seismic forces, and improper bearing operation are a few of the factors that contribute to the distress of reinforced concrete bridges. The world's highest mountain areas are facing many environmental challenges such as rapid population growth, environmental degradation, Climate Change (CC), and glacial melting, resulting Glacial Lake Outburst Flood (GLOFs). The GLOFs event happens when ice is unable to hold the restraining end moraine wall of loss material from the glacier, often underlain by debris, and as a result, the sudden

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releases of water from impounded Lake Outburst floods. It can cause loss of life, injury, serious damage to property communities.

Throughout the past thirty years, Pakistan's urbanization has accelerated due to economic growth. Urban infrastructure, such as bridges, roads, water supply and sewage systems, electric and electronic pipes, and metro systems, are continually in demand because of urbanization. Unfortunately, because to natural disasters (such as earthquakes, floods and ground subsidence) and a lack of appropriate knowledge and sustainable management layer concepts, the service life of these infrastructure structures frequently falls short of the planned life. Some facilities collapsed during the construction period, while others failed during their service life [3-4], which had harmful impacts on the social community and environment [5]. Bridge failures are one of the most severe infrastructure problems facing the world today and usually cause significant economic losses and casualties. This has elicited a considerable amount of attention from designers, engineers, researchers, and policy makers. Bridge failures pose an imminent threat to life and property during their service life, which reinforces the need to implement updated sustainability assessments and optimal risk mitigation procedures [6].

One aspect of studying engineering failures is the relationship between the failure and the growth of engineering knowledge, which ensures the sustainable development of society [7]. The engineering profession must extract as much information as possible from these failures. The lessons from these bridge failures should be thoroughly studied to ensure the future safety, durability and construction cost of bridges. In response to a large number of bridge failures, researchers have focused on three aspects of bridge failure: (i) the general situation and development trend of bridge failures; (ii) bridge safety evaluation based on structural monitoring and mechanism analysis, and (iii) risk assessment and control for sustainability and environment health. The general situation of bridge failures is illustrated by failure data involving location, occurrence time, life and economic loss [8,9]. However, the likelihood and degree of uncertainty when a mysterious event leads to system failure is difficult to directly measure by experts [10]. Therefore, it is necessary to focus on facilitating bridge failure risk assessment and establishing a sound bridge management system.

The existing bridge management system (BMS) includes several methods [11]: (i) the grey system theory and Bayesian networks; (ii) analytic hierarchy process (AHP) and fuzzy comprehensive evaluation (FCE); (iii) comprehensive evaluation based on onsite inspection. The grey system theory and Bayesian networks are used to predict bridge technical conditions [12]. The current bridge management regulations in Pakistan are mainly used in comprehensive evaluation based on onsite inspection[13]. Recently, fault tree analysis (FTA) and strategic environmental assessment (SEA) modern practices have been expanded in project management for sustainability [14-15]. Fault tree analysis (FTA) and strategic environmental assessment (SEA) are used to formulate the comprehensive management guidelines. FTA is a reasonable and appropriate approach for fault identification, which can help in the identification of failure paths [14]. SEA is an effective tool for integrating principles of society, economy and environment, which represents the three pillars of sustainability. The detailed description of the decision-making process based on Bridge using SEA, which demonstrated that the SEA is a good criteria for large-scale projects. Although extensive studies have been carried out on the methods of management systems, the risk assessment of bridge infrastructures is still of keen interest.

2. Study Area

Hassanabad is a small village adjacent to Aliabad city, Hunza, Northern Pakistan. Karakorum Highway crawls through the study area. Hassanabad ravine (Nallah) originates from Shishper and Mochowar glaciers, and runs toward the south, joining with the adjacent Hunza River. The total watershed area is approximately 359 km2 (Fig.1). The study site (36° 15′ – 36° 30′N latitude, 74° 28′ – 74° 39′ E longitude) comprises the Hassanabad watershed in district Hunza, north Pakistan. The Shishper Basin is extremely prone to Glacier lake outburst flood because of the swift advancement of Shishper Glacier and blockage of HassanabadNallah[16-18]. An integrated approach was adapted to assess the potential risk of Shishper GLOF by integrating Geomorphometric assessment, land cover change and temporal analysis, physical vulnerability assessment and community perceptions on Shishper glacier. A Glacial Lake Outburst Flood (GLOF) has destroyed and swept away the strategically important Hassanabad Bridge on the Karakorum highway in Hunza, district in Gilgit Baltistan Pakistan.

3. Objective of Case Study

This paper focuses on bridge management in terms of sustainability, in which data analysis and a case study on the managerial reasons for bridge failure and multiple impacts are investigated in detail. In order to reveal the managerial reasons, a summary of bridge failures is presented. The objectives of this paper are: (i) to investigate the managerial reasons for bridge failure using FTA and the failure-induced environmental impact using SEA; (ii) to propose mitigation countermeasures for bridge failures in managerial aspects, and (iii) to provide a reference for governments to maintain sustainability and safety measures.

Case Study of Hassanabad Bridge Collapsed

The main bridge connecting China and Pakistan via Karakoram highway. The Hassanabad bridge part of the China Pakistan Economic Corridor (CPEC. The bridge was located in Hunza Tehsil of Gilgit-Baltistan region of Pakistan Occupied Kashmir (POK) [18]. This bridge was first constructed in 1972 and it connects ShinakiHunza with KarimabadHunza. This bridge was the only main source, which connects Gilgit Baltistan with China via Karakorum highway. In Hassanabad, Karakoram Highway passes over a side stream of the Hunza River, which is fed from the Shishpar Glacier, located about 10km above Hassanabad. It was over the Hunza River's tributary, between Aliabad and Murtazabad. Hassanabad is also gateway to HachinderChish (7162.4 meters) [19]. Two of the old Hunza tribes are present in Hassanabad, Ganishkutz and XhillGanishkutz. Gilgit-Baltistan is a part of the erstwhile princely state of Jammu and Kashmir and is under the occupation of Pakistan since 1947 [20].

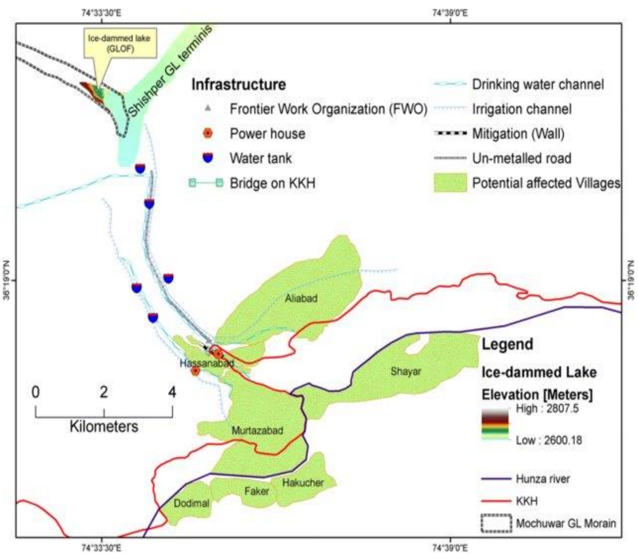

Figure 1 Hassanabad Bridge Map

The China Pakistan Economic Corridor (CPEC), the flagship of China's Belt and Road Initiative (BRI) traverses through this region, which has a special constitutional status in Pakistan. CPEC starts from Gwadar in restive Baluchistan, then passes through Gilgit-Baltistan, and terminates at Kashgar in China's Xinjiang region. Since the beginning of ambitious CPEC, environmentalists and activists have been issuing warnings of major disasters in the Gilgit-Baltistan region of POK. Gilgit-Baltistan is home to some of the world's highest mountain ranges [18].

Extreme weather conditions and abrupt temperature rise in northern areas of Pakistan, A Glacial Lake Outburst Flood (GLOF) has destroyed and swept away the strategically important Hassanabad Bridge on the Karakorum highway in Hunza, district in Gilgit Baltistan Pakistan. Several small cracks appeared in an arch ring in the middle of Hassanabad Bridge, where a slight dislocation was observed in the west abutment. Therefore, the bridge underwent significant maintenance in November 2015. Partial bridge deck girders were repaired, and slope-type protective fences were installed on both sides of the road.

The city of Gilgit Baltistan was affected by heavy rain suffered severe flooding at several locations. According to the information provided by the local traffic bureau, the average daily traffic flow in the month before the collapse was approximately 7000 vehicles per day.

4. Collapse Process and Analysis

This GLOF incident in Hunza occur due to rapid meltdown of Shishper Glacier. This induced erosion of glacial lake outburst flooding has damaged over 52 houses and KKH from some points [18]. Furthermore, hundreds of trees cultivated land and two hydropower plants were got effected as well, 22 houses have been vacated and residents have been shifted to safe place. According to survey, the local population is not exposed to any sort of risk. However, the shortage of water, food and petrol in the areas, which connects Gilgit city to other valleys of the region, is a serious concern. Houses, orchards, powerhouses, and fiber optics have also been damaged in the area. The bridge collapse had destroyed the irrigation system and provision of clean drinking water in Aliabad city and Hassanabad village, while it also caused damage to two grid stations. Meanwhile, the NHA chairperson and design engineer on Saturday had visited the damaged bridge being renovated in Hassanabad.

Impacts of the destruction of this bridge will be both economic and strategic as both Pakistan and China are dependent on this bridge for trade. Hunza is gateway of CPEC in the region so as this bridge is a lifeline for all smooth trade activities. Secondly, if we talk about local economy, the incident will affect the local traders as well because they are engaged with border trade since long. It also affects the region's tourism industry as the domestic and international tourists would not be able to reach Hunza and it will put a stop on the earning of many people who are attached with tourism industry.

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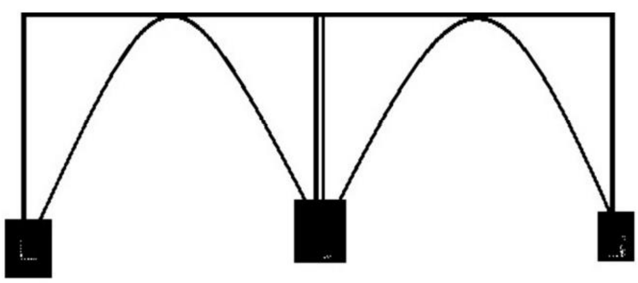

Figure 2 Hassanabad Bridge Sketch

Figure 2 illustrates the structure of Hassanabad Bridge. As shown in this figure, the structure of the bridge consists of piers and two abutments

Figure 3 shows the real picture of the Hassanabad Bridge before the collapse.

Figure 4 shows the picture of the Hassanabad Bridge after the collapse.

Figure 3 Hassanabad Bridge before Collapse

Figure 4 Hassanabad Bridge after Collapse

The management and rescue departments of the local government launched emergency rescue immediately after the collapse. According to the monitoring video, it was determined that the trigger cause of the accident was an arch foot failing at Pier, which caused the collapse of the arch ring in span 2. The collapse of span 2, caused a chain reaction that resulted in the new plastic hinge of the arch ring. Finally, it formed a mechanism that caused the second span to collapse and fall into the water. Fortunately, the first and the piers were rigid, which resisted the unbalanced thrust caused by the collapse of the second spans, and the bridge did not collapse completely.

The impact of river water scouring on Hassanabad Bridge over the past 10 years cannot be neglected. The previous studies indicated that scouring, which often occurs at abutments, piers and other bridge substructures has a significant impact on bearing capacity. It can be inferred, under the long-term scouring of flooding, the sediment around the upstream surface of Pier foundation was taken away and the depth of the foundation of Pier on upstream side was inadequate, resulting in the inclination and further weakening of the bearing capacity of Pier.

Flood Collapse of the Bridge

As can be seen in Fig.4, the channel that is directing the floodwaters to the bridge is not straight. When the floodwater flows and arrives at the flat lands, a relatively wide delta is formed. However, when the Bridge narrowed the width of the delta from about 70 meters to only about 30 meters, presumably to save in the costs of construction. As a result, the floodwaters, instead of flowing unhindered through the delta and being dispersed into the floor of the valley, ended up forced to make a 90-degree turn to the right and flow about 100 meters' parallel to the Interstate Highway 10 and then make another 90-degree turn, this time to the left and pass under relatively short bridge. This turning of flood path without carefully studying the pressures that will be exerted on the embankment and bridge foundations and piers caused the collapse of the bridge.

Failure Cause of Arch Bridge Analysis

Scouring of foundation is considered primary causes of failure as it occupies around 60% of total bridge failure together with other hydraulic causes. This bridge collapsed mainly due to scouring of soil below the foundation. Scouring of foundation can occur all over the year, it reaches peak when flood comes in water body over which a bridge is spanning. History of bridge failure indicates scouring of streambed around abutments and piers of bridge, led to maximum bridge failures. Scour at bridges is a very complex process. Scour and channel instability processes, including local scour at the piers and abutments, contraction scour, channel bed degradation, channel widening, and lateral migration, can occur simultaneously. To further complicate a mathematical solution, mitigation measures, such as riprap, grout bags, and gabions, may be in place at the abutments and piers. Any mathematical model would have to account for these structures as well. The interactions of the processes of local scour, contraction scour, channel bed degradation, channel widening, and lateral migration are unknown. The total vertical erosion at the bridge is then simply the sum of the scour and bed degradation. Because no other formation is available, this assumption provides a conservative estimate. Lateral channel instabilities are typically considered separately from scour and bed degradation, and the estimate of their effect on bridge foundations is often based on judgment and experience. The interactions of scour and channel instabilities are very difficult to predict. Certainly, the processes may not be independent but rather related to each other and the resulting impact on the bridge.

5. Analysis Methods

The methodology for the management analysis of bridge failure includes fault tree analysis (FTA) and strategic environmental assessment (SEA). Figure 5shows a schematic flow chart for bridge failure analysis used in this paper. First, a detailed analysis of the failure process was adapted to analyze the causes of failures. For direct reason analysis, numerical simulation, such as a finite-element method (FEM), was performed to identify the trigger cause and quantitatively verify the bridge failure process. Since this study pays more attention to the managerial reasons based on the technical analyzed results, the detailed technical analysis was used. Management cause as an indirect reason may be more significant than the technical reason, so FTA and SEA were used. Based on technical analysis, FTA was used to show the overall causes of the Hassanabad Bridge collapse and further classify the failure causes qualitatively. SEA was used to assess the management risks of bridge management and provide guidelines for bridge sustainability. SEA analysis was adopted based on six principles for SEA effectiveness to assess the risk probability scores in bridge sustainability. Furthermore, combined with FTA, management analysis using SEA proposed countermeasures and management guidelines for decision-making in development projects, which is pivotal for improving sustainability in terms of society, environment and economy.

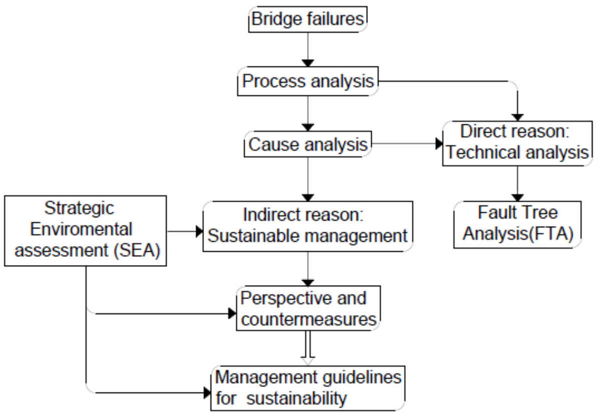

Figure 5 Bridge Failure analysis process

Fault Tree Analysis (FTA)

FTA was used to reveal the collapse reasons of Hassanabad Bridge. Due to difficulties in conducting field-tests to investigate the bridge's collapse and measured data collection, numerical analysis was performed. The numerical simulation method was performed to back-analyze the failure process and identify the failure causes. Before FTA, FEM numerical analysis was conducted using Ansys 17.0 to simulate the finite element model (FEM) of collapsed sections (Span 2) of the Hassanabad Bridge. The detailed FEM simulation followed a similar method to that introduced. To simulate the failure at the arch foot of Span 2 near Pier, the stiffness of the material element at the arch foot was weakened to about one thousandth of the strength of other elements.

According to the first strength theory, the main failure factor of brittle materials such as concrete is that the maximum tensile stress exceeds the material limit. Therefore, in this paper, the first principal stress, the deformation at the collapse time of Span 2 is also similar to the actual situation.

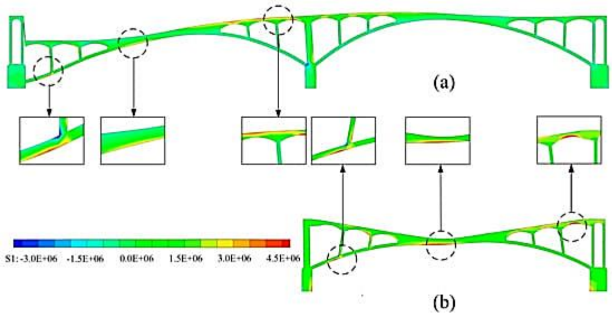

Figure 6 Maximum Principle stress and deformation diagram of the Bridge Model

Figure 11. Maximum principal stress and deformation diagram of the bridge model when (**a**) Span 2 begins to collapse (**b**) Span 2 has collapsed completely.

Based on the FEM results and process analysis, an FTA diagram was simulated. The FTA structure is illustrated in Figure 7. According to the FTA structure, the top event is the collapse of Hassanabad Bridge. The basic events at the bottom consist of the causes of the collapse. The collapse of Span 2 and Pier are intermediate events. All events are connected by "AND" and "OR" symbols logically. Arch foot failure directly resulted in the collapse of Span 2. With the demand of social development, the changing external circumstances such as the constant increasing of the traffic volume value and river flow value increased the traffic load and reduced the bearing capacity. Additionally, inadequate management measures including decision errors and lack of regular inspection had a long-term effect on the bridge structure. Hence, the collapse of Span 2 and the setting of flexible Pier caused the collapse of Span 2. Due to aggravated river scouring and inadequate reinforcement measures, Pier collapsed. It can be illustrated that the arch foot failure is a crucial technical factor leading to the whole collapse of Span 2. In addition to normal events for bridges like river scouring, setting of the flexible pier and ever-changing circumstance, inadequate management measures are potential comprehensive factors causing the collapse. Moreover, when the collapse happened, the bridge had been in service for nearly 50 years, and the load on the bridge deck was small, which confirms that the management of bridge engineering is worth further study.

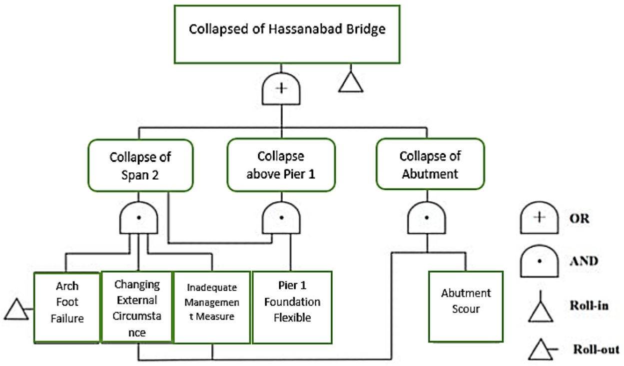

Figure 7 Main Fault Tree Analysis of Hassanabad Bridge Collapse

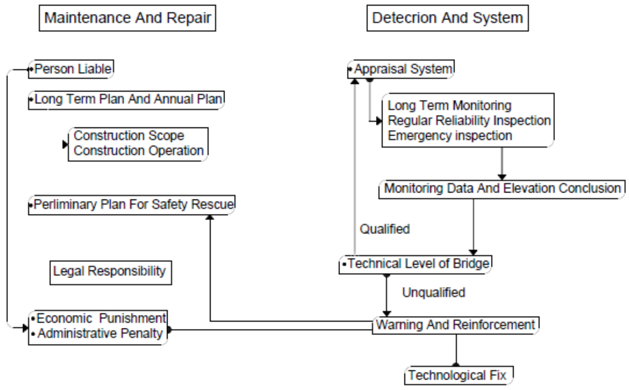

Figure 8SEA Management measures for the inspection of Hassanabad Bridge

SEA Analysis

Since SEA is a good practice criteria for large-scale projects, in the following context, SEA analysis was adopted based on six principles in contrast to the management measures of urban bridges issued.

Figure 8 shows the main content diagram of the management measures for the inspection, maintenance and repair Hassanabad Bridges. Comparing articles conducted SEA assessment one by one between the established management measures and the field implementation. Table 1 shows the SEA evaluated results of Hassanabad Bridge based on regulations of the National Highway Authority of Pakistan. The score of SEA is given according to the following categorized management factors: (1) sustainability principles were taken into account in the bridge design phase, but the sustainability principles were been adjusted and improved during operation management and maintenance with the change of environment during bridge service; (2) insufficient monitoring of bridge structural stability during bridge service. The construction scope and operation were not well controlled; (3) despite the promulgation of relevant regulations on sand mining in rivers, the punishment for illegal sand excavation by regulatory authorities is insufficient and sand excavation has a continuous cumulative impact on the environment. The link between administrative law enforcement and criminal justice should be strengthened. (4) The impact of environmental integrity on decision-making and the assessment of the environment is not considered accurately. During flood season, the storage capacity of the reservoir was not considered and the emergency inspection of flood discharge of reservoirs on downstream bridges was not implemented. The construction scope of reservoirs (infrastructures near the bridge was not well controlled; (5) a lack in effective management decision making and measures. The bridge had been put into use before the hidden danger of bridge was solved completely. Hassanabad Bridge underwent major maintenance in November 2019. However, the partial collapse accident occurred at Hassanabad Bridge in 2019. Bridge maintenance was carried out, but the expected results were not achieved.

6. Failure Analysis of Flood Collapse of the Hassanabad Bridge

This study summarizes the failure analysis to understand the cause of this collapse, and to learn engineering lessons from this collapse. The model then was subjected to simulated floodwaters until the bridge collapsed.

By studying the results, it was concluded that the collapse occurred due to combination of five factors:

1) The bridge had a length of about half of the width of the flood path, creating a bottleneck on the path of the flood.
2) Floodwaters before reaching the bridge made an “S” curve turning right and then left before going under the bridge, which resulted in washing the soil under the east abutment.
3) The east abutment was supported on fill soil without piles, therefore when the supporting soil under the abutment washed away; it could not be supported and collapsed.
4) The wing walls in the abutment were perpendicular to the floodwaters, resulting in floodwaters pushing the abutment and collapsing it.
5) When the abutment lost its supporting fill-soil and was pushed by flood and collapsed, the deck slab of the roadway supported on it also collapsed.
6) A Glacial Lake Outburst Flood (GLOF) has destroyed and swept away the strategically important Hassanabad Bridge.

7. Discussion: Guideline of Sustainable Management

To avoid similar infrastructure failures in the future, in view of the above causes in the bridge collapse case, both design countermeasures and management guidelines are proposed.

The design countermeasures can be further divided into static and dynamic retrofit solutions. As static retrofit solutions of bridges, specific materials like carbon fiber-reinforced concrete can be applied to the vulnerable parts of bridge arch feet, bridge columns, pier connections, etc. This helps to resist impact and scouring, which can prevent or reduce sudden accidents. It can also improve the risk resistance under extreme conditions. Specifically, for arch bridges, the design of rigid piers is extremely important in multi-span continuous bridges, because it can effectively resist the unbalanced thrust caused by the collapse of one-sided arch spans and thereby prevent the continuous collapse [21-22]. As dynamic retrofit solutions of bridges, reasonable dynamic isolation approaches like inelastic hinges and other devices can prevent and reduce bridge failure caused by earthquakes. Multi-attribute utility theory (MAUT) can provide a general approach to evaluate the sustainability of bridges in terms of seismic retrofit optimization and aid the decision maker in making informed choices.

To improve the management of bridges and other infrastructures, considering social, environmental and economical sustainability, the following management guidelines for bridges and other infrastructures based on the implemented analysis are provided as shown in Figure 9.

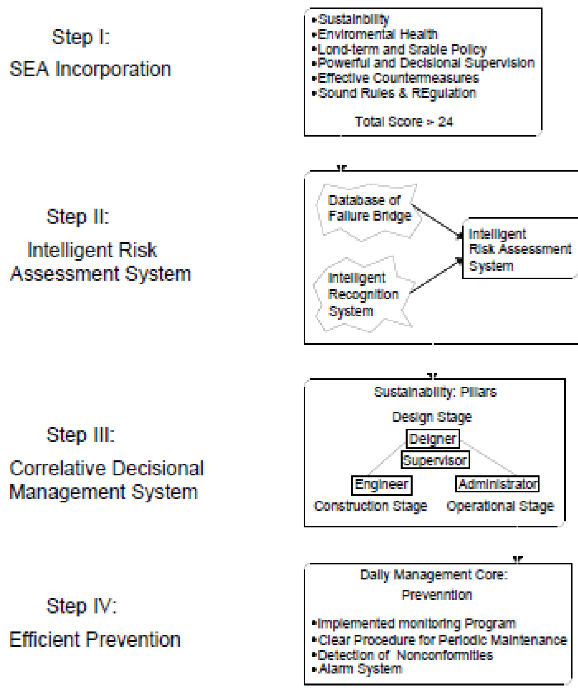

Figure 9 Sustainable Management Guidelines

Step I

Improve the management system with modern and adjusted SEA principles; SEA is recommended to be incorporated into comprehensive project management, the total score of the SEA should be higher than 24;

Step II

Establish and update an intelligent risk assessment system [23]. Today's risk assessment performed by inspectors is insufficient and inconsistent. Intelligence recognition systems that are applied to the unified database for failed bridges can assist in improving the accuracy and effectiveness of the risk assessment. Hence, knowledge-based expert systems (KBE) and artificial intelligence (AI) systems are the key technical procedures for the intelligence recognition systems, which can be used for accurate and reliable post-disaster condition assessments like crack and stress concentration identification.

Step III

Adopt the correlative decisional management system. The adaptive management system consists of the designer in the design stage, the engineer in the construction stage, the administrator in the operational stage, and the supervisor during the whole period. Each level of management has corresponding responsibilities and should take the three pillars of sustainability into consideration. It is crucial to establish a correlative decisional and cooperation mechanism for the whole management.

Step IV

Adopt efficient and diversified means of prevention, which are the essence of daily management. The monitoring and clear procedures for periodic maintenance are an important part of preventing failures. In addition, the detection of nonconformities and alarm systems play a major role in emergencies, helping to establish a complete daily management system.

Conclusions

This paper investigated the managerial reasons for bridge collapse using FTA and failure-induced environmental impacts using SEA. Statistics on recent bridge failures in Pakistan were analyzed. Moreover, management guidelines were proposed based on SEA evaluation. The main conclusions are summarized as follows:

1) The statistical analysis on the bridge failures showed that about 70% of bridge failures were due to anthropic factors, which is a much larger proportion than those caused by natural factors (30%). These safety accidents cause great losses of life and property, which expose the problems in bridge construction management hindering the sustainable development of society.
2) Hassanabad Bridge failure was used as a case study to analyze the reasons relating to a lack of sustainable management. The FTA results show that the arch foot failure was the direct triggering cause of the Hassanabad Bridge collapse. Moreover, a lack of real-time monitoring, risk assessment and other management issues were

potential comprehensive factors causing the bridge collapse.

3) The SEA method was conducted to evaluate the management risk of Hassanabad Bridge. The low scores illustrated the high risk and negative impact on the community for this case. It is verified that SEA is an effective method for integrating sustainability principles related to societal, economic, cultural, human health and environmental factors in decision making relating to the development of bridge projects.
4) To improve the bridge sustainability, the following management guidelines based on SEA were proposed: (i) a management system improved by SEA; (ii) an intelligent risk assessment system; (iii) perfecting the correlative decisional management system; (iv) efficient and diversified means of prevention.

Establish, record and have available to the examining team full details of foundation depths. If these are not available from 'as-built' drawings, core drilling may be required. Once this information is available, ensure that it becomes routine to consider it when looking at under- water reports and scour data the glacial lake outburst phenomena. In 2022, a "Scaling up of Glacial Lake Outburst Flood Risk Reduction in Northern Pakistan Project" was continued in 1929, a GLOF from the Chong Khumdan Glacier in the Karakoram caused flooding on the Indus River 1,200 km downstream (a maximum flood rise of 8.1 m at Attock.

Develop a more sophisticated way of reviewing riverbed soundings. These are routinely taken at each underwater inspection but for them to really predict the likelihood of a bridge being affected by scour then the data should be well handled. The results should show changes in time (by comparisons with previous soundings) and geographical changes. The latter will indicate if bed levels at the bridge are lower than might be expected when compared with upstream levels and will show any migration of the main channel. In the case of Stay Thorpe, for instance, only by plotting bed contours over a significant length of the river could the pattern of scour be established.

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